

SOLID PROPELLANT COMBUSTION DIAGNOSTICS AND
AUTOMATED DATA RETRIEVAL FROM HOLOGRAMS*

J. M. Glenn, K. J. Graham, R. K. Harris, Y. Lee, D. W. Netzer and J. P. Powers
Naval Postgraduate School
Monterey, California

ABSTRACT

High speed motion pictures, holography and measurements of scattered laser light are being used to study the behavior of particulate matter in the combustion products of solid rocket propellants. An automated data retrieval system for obtaining particulate data from reconstructed holograms is also under development. Progress on all phases of this continuing effort are discussed.

INTRODUCTION AND OVERVIEW

The goal of the investigation to date has been to develop and compare experimental techniques that can be used for obtaining quantitative data on the effects of propellant properties, operating pressure, and nozzle geometry on the behavior of metallized particulates within the grain port and nozzle of solid propellant rocket motors. These data are needed in order to (1) improve solid propellant performance predictive capabilities, (2) provide needed input to current steady-state combustion models of AP-aluminum interactions, and (3) provide in-motor particle size distributions which will allow more accurate predictions of damping in stability analyses. The techniques employed have been high speed motion pictures of strand burners and slab burners in a cross-flow environment, SEM analysis of post-fire residue (strand, slab, and motor), determination of D_{32} across the exhaust nozzle using measurements of scattered laser light, and holograms of burning propellant strands and slabs in a cross-flow environment. In addition, considerable work has been directed toward development of automatic data retrieval methods for obtaining particle size distributions from holograms taken of the combustion of solid propellants. The holographic effort is a two-part problem. Techniques must be developed for obtaining good quality holograms of burning solid propellants in a realistic environment. However, these holograms are of limited value unless the particle size data can be obtained from them in a reasonable time period. This requires development of computer-aided image analysis techniques. Once developed, these techniques/ diagnostic methods could be readily employed for obtaining the needed data discussed above from a series of tests in which propellant composition, motor geometry, and operating environment are systematically varied.

All experimental techniques have been successfully developed to the point where they can be employed (within restricted ranges) to obtain particulate size data from a series of specially formulated propellants. It has not been the purpose of the investigation to date to obtain data from specific current propellant compositions, but rather to demonstrate the ability to obtain the data. Most of the propellants employed produced particulate diameters in the gas phase that were essentially identical to those cast in the propellant. Thus, wide ranges in particulate size were neither expected or observed in the films or holograms.

In previous efforts the motion picture and holographic techniques were successfully demonstrated using propellant strands burned at operating pressures of 34 and 68 atm. and with up to 15% aluminum. Fourteen μm resolution was obtained in the high speed motion pictures with a 1.12X magnification (and very small depth of field) and an eleven μm resolution was obtained in holograms. In addition, initial determinations of D_{32} were made using measurement of scattered laser light at the exhaust of a small rocket motor.

Several needed improvements to the diagnostic technique were required. These were:

(1) Use of laser light illumination and narrow pass filters with the high speed motion pictures in order to eliminate the flame envelopes around the burning particles.

(2) Use of photo-diode linear arrays in place of a translating photo-diode in order to improve the accuracy of the measurements of scattered laser light.

(3) Incorporation of a second diode array at the nozzle entrance so that particulate changes across the nozzle could be measured.

(4) Increasing the power density that reaches the holographic plate by changing both laser and 2-D motor design.

*This work was performed under contract Number F04611-84-X-0001 with the Air Force Rocket Propulsion Laboratory, Edwards, California.

The high speed motion picture investigation of burning propellant strands was continued using a combination of monochromatic and white light illumination. The final illumination method uses two side/front illumination sources during one test, a 2500 watt white light and 0.8 watt laser light at 488 nm. With this illumination method a rotating filter disc is placed between the combustion bomb window and the camera lens. This provides alternating frames with high intensity white light illumination and filtered 488 nm illumination. The front-lighted monochromatic source yields films in which the particle flame envelopes are eliminated as desired. The camera has been mounted on a mill bed to provide both stability and precise focusing.

A dual beam apparatus for measuring scattered light was developed to simultaneously measure particle size (D_{32}) at the entrance and exit of an exhaust nozzle of a small solid propellant rocket motor. The diameters were determined using 1024 element linear photodiode arrays to measure diffractively scattered laser light. He-Ne illumination was used at the nozzle exhaust but significant 632.8 nm radiation within the motor combustion zone required the use of argon laser (488 nm) illumination in that region. Early measurements were successful at both locations. However, the presence of char agglomerates (binder and inhibitor) in the exhaust products significantly alters the "measured D_{32} ". Two modifications were made to improve this diagnostic technique; improvement of the propellant and improvement of the instrumentation. Rather than one sweep of each of the diode arrays during one firing, eight sweeps of one and four sweeps of the other are now made. This was made possible by expanding the memory of the multiprogrammer and by utilization of the HP9836A computer in place of the HP85. AFRPL fabricated GAP propellants (to replace the HTPB propellants which were originally used) in order to provide "cleaner" exhaust products. In addition, the optics and data acquisition methods have been modified to improve accuracy. Transmitted light is now blocked with a "stop" so that the non-deflected laser beam can be positioned directly on the first diode of the array. Interactive graphics has also greatly improved the speed and accuracy of the data reduction. A cylindrically perforated, aft-end uninhibited grain is currently being used in an attempt to further eliminate inhibitor char in the exhaust gases.

Efforts have been directed at improvement of the quality of the holograms which are obtained in the 2-D motor in the presence of cross-flow. The propellant slabs are currently bonded to borosilicate glass side plates and burned within the combustion bomb.

Various techniques have been suggested for the automatic retrieval of particulate diameter data from reconstructed holograms, ranging from complete digitization to man-in-the-loop optical methods. A reasonable near-term solution appears to be a combination of both optical and digital methods. NPS requested and obtained a Quantimet 720 from BRL. Initially the system was installed and simple measurements were made for training purposes on photographs of a holographic reconstruction of a strand burning at 500 psi. Current efforts are being directed at obtaining data directly from a reconstructed hologram.

DETERMINATION OF PARTICULATE SIZE USING MEASUREMENTS OF SCATTERED LASER LIGHT

INTRODUCTION

The method used in this continuing effort was the diffractively scattered light technique. The diffraction patterns of light scattered by particles are analyzed to determine the volume-to-surface mean diameter. This method has the disadvantages that size distributions cannot be easily determined and particles larger than some threshold size will not be detected due to the exceedingly small angles at which they scatter light. However, it has the advantage that it is non-intrusive and, in theory, can be used in the internal motor environment. Previous efforts at the Naval Postgraduate School^{1,2} showed that propellant composition can limit the application of the technique. Large particulate combustion products in the flow made particle size data difficult to obtain. This was especially true if only one measurement of the scattering profile was made during a test firing.

To address this problem in the present study several improvements were made. A cleaner burning propellant was obtained to reduce char agglomerates in the exhaust products. A more statistically valid data sample (multiple measurements during a single test) was made possible with added memory in the data acquisition equipment and a pacing circuit which allowed full use of this memory. Data reduction was also improved with a Hewlett Packard 9836S computer combined with a more recently developed approach to particle sizing presented by Buchele³.

The completely general theory of scattering was developed by Mie and is presented by Van de Hulst⁴. The light scattering characteristics for spherical particles of any size are fully described in a mathematical format. The Mie scattering functions contain Legendre polynomials and spherical Bessel functions and fully treat the phenomena of reflection, refraction, diffraction, and extinction.

For particle sizes much smaller than the wavelength of light, the Mie equations simplify to what is called Rayleigh Scattering.

The study of particle behavior in solid propellant rockets normally is concerned with particles having diameters much greater than the wavelength of visible light. Scattering by these larger particles is described adequately by Fraunhofer diffraction.

The ringed diffraction pattern generated by a hole in a mask, or a number of particles of the same size is described by the equation:

$$\frac{I(\theta)}{I(\theta=0)} = \left\{ \frac{2J_1(\alpha\theta)}{\alpha\theta} \right\}^2 \quad (1)$$

where:

$I(\theta)$ describes the intensity of the scattered light at an angle theta (θ),

$J_1(\alpha\theta)$ is the Bessel function of the first kind, and

$\alpha = \frac{\pi D}{\lambda}$ is the particle size parameter for diameter D and wavelength of light λ (λ).

Measuring the particle size for a monodispersion can be accomplished by measuring the angular position of a dark or bright ring in the diffraction pattern.

The above method is not used for polydispersions since the discrete rings are not observed. However, Dobbins, et al.⁵ introduced a significant improvement in the diffractively scattered light method of particle sizing. They found that although the method was not directly able to determine distributions of sizes, the volume-to-surface mean diameter defined by

$$D_{32} = \frac{\int_0^\infty N_r(D) D^3 dD}{\int_0^\infty N_r(D) D^2 dD} \quad (2)$$

(where $N_r(D)$ is a distribution function describing the proportion of particles with diameter (D) in the sample) could be accurately measured. A curve for sizing polydispersions was presented.

More recently, Buchele³ has presented a good summary of experimental techniques for particle sizing by measuring diffracted light. One point of interest in his report is that he represents the scattering profile for a polydispersion with a function which closely approximates the curves of Ref. 5.

$$\frac{I(\theta)}{I(\theta=0)} = \text{EXP} - (.57 \alpha \theta)^2 \quad (3)$$

This function and the curve from Ref. 5 were both used in the present study.

EXPERIMENTAL APPARATUS

A schematic of the apparatus is presented in Fig. 1. The light scattering equipment was mounted on two optical benches; one for measurements in the nozzle exhaust and one for measurements within the motor cavity. The light sources employed were eight (8) milliwatt helium neon and argon lasers for the exhaust and motor paths respectively.

Each beam passed through the appropriate test volume and was then intercepted by a physical stop located in front of its set of receiving optics. The further the stop was placed from the test section, the smaller the angle at which scattered light could be measured. In the present set-up light scattered at a minimum angle of approximately .008 radians could be measured. Light scattered at angles greater than this was not intercepted and continued past the edges of the stop. The stop served to keep the transmitted beam out of the measuring optics and, thus, reduce extraneous light. The stops also improved optical alignment.

The scattered light passed through a narrow pass filter which admitted only the laser light. An objective lens of 50 centimeter focal length was located behind the narrow pass filter. This lens imaged the scattering profile of the particles in the test section onto a photodiode array. The shadow of the beam stop was also imaged since the stop was between the test section and the objective lens.

The photodiode arrays each contained 1024 silicon photodiodes on a single chip with 25 micron spacing. The accompanying circuits provided a "sampled and held" output which was essentially analog except for switching transients. The actual sampling time of the array was about 34 milliseconds with a delay between scans of about 6 milliseconds.

The 50 centimeter focal length of the objective lens combined with the dimensions of the diode array provided a half-angle field of view of about 3 degrees for mediums of refractive index near unity.

DATA REDUCTION

Raw data was plotted on the CRT where any obviously erroneous scans could be excluded from further reduction. The valid scans were averaged to obtain a mean scattering profile. The mean intensity profile taken before particles were introduced was then subtracted from that taken with particles present. This corrected for the characteristics of individual photodiodes and extraneous light which was independent of the particles.

A symmetric moving-average-type of digital filter was then applied to the profile to achieve some smoothing. This type of digital filter was chosen for simplicity and because it does not have the phase lag of analog filters. Preserving the phase of the data was necessary to retain angular resolution. Another advantage of filtering in the software rather than hardware was that raw data files remained unmolested.

The scattering profile was then analyzed using interactive graphics. A scattering profile has to be normalized in order to be compared to the theoretical curves for polydispersions. The scattered light intensity on the centerline of the beam is the correct value to use for normalization but is unmeasurable due to the presence of the (blocked) transmitted beam.

The other unknown was the particle size. These two variables (centerline scattered light intensity for the measured profile and D_{32} for the theoretical profile of normalized intensity vs. angle) were adjusted using interactive graphics until the curve for polydispersions coincided with the data. In this way the mean diameter of particles was determined.

The second reduction technique used was the direct application of the method presented by Buchele³. The approximate equation for the polydispersion curve (equation (3)) was applied at two points of the scattering profile. This gave:

$$I_2/I_1 = \text{EXP} -D^2[(\theta_2^2 - \theta_1^2)(.57 \pi/\lambda)^2] \quad (4)$$

Solving this for the diameter gave:

$$D = [-\ln(I_2/I_1)(\lambda/.57\pi)^2/(\theta_2^2 - \theta_1^2)]^{1/2} \quad (5)$$

The computer was used to sweep through the data using many values of θ_1 , along with several angle ratios to determine θ_2 . The results were displayed graphically as particle size vs. θ_1 for each angle ratio (θ_2/θ_1).

CALIBRATION AND EVALUATION

The geometry of the apparatus used in the initial investigations² is compared with that of the present study in Fig. 2. In the present study stops were used to intercept the beam before it reached the receiving optics. These stops provided several advantages. A high intensity beam could be used while producing little extraneous light. Also, optical alignment was also improved. This reduced error in angle measurement.

Calibration of the apparatus was accomplished by measuring D_{32} of various particles of known size. Polydispersions of glass or polystyrene spheres and aluminum oxide powder were suspended in water within a Plexiglas container. A scanning electron microscope was also used to photograph each particle sample.

Calibration results are summarized in Table I. Figs. 3 and 4 present typical calibration results.

These tests showed that the apparatus had two distinct modes of operation. If the particle concentration was very high, or if large particles dominated the polydispersion, many of the diodes at the smaller angles would saturate. This left only the data at larger angles useable. When many diodes saturated, the theoretical curve given by Dobbins, et al.,⁵ was used to determine size. This was done because this curve was valid for the larger angles and lower relative intensities. The curve from Buchele³ was not valid for values of the beam spread parameter greater than three (3).

TABLE I CALIBRATION RESULTS

Particle Material	Particle Size microns	Equation (1) Calculated D_{32} microns	Scattering Measurement D_{32} microns	Error microns
Polystyrene	3 to 6	4.7 **	4.5	.5
Polystyrene	6 to 16	10.2 **	7.9	2.3
Polystyrene	15 to 30	21.6 **	21	.6
Glass	37 to 44	38. *	40	2.
Glass	53 to 63	54. *	54 to 58	0 to 4
Glass	1 to 37	25. *	28 to 30	3 to 5
Aluminum Oxide	≈ 25		28	-----
Aluminum Oxide	≈ 50		45	-----

* From SEM Photos

** From Manufacturers Data

For low particle concentrations and/or small particles the data proved more accurate at the smaller angles. If no diodes were seen to saturate then one knew the measurement was in the higher intensity part of the center lobe. Here the curve given by Buchele³ was quite satisfactory for sizing.

The smallest particles tested were five, ten, and twenty micron polystyrene spheres. The bright rings for these particles occurred at angles too large for the apparatus to measure. For these samples the diodes did not saturate. Both the Gaussian curve fit and the two angle method were used to obtain D_{32} . These results were especially consistent. It should be noted that the two-angle method uses the equation for the Gaussian. If the measured profile matched the Gaussian exactly, then D_{32} would be the same for any θ_1 and angle ratio (θ_2/θ_1) employed.

The results of the calibration tests showed that the apparatus is capable of accurately measuring mean particle size for a broad range of mean diameters. It was found that the technique was most accurate if the theoretical profile fit or if the two-angle method were applied at the smallest possible scattering angles.

Another concern about the measurement technique is the effect of the index of refraction of the exhaust gases in which the particles are present. To examine this, the 6-16 μ m polystyrene sphere data was used to find D_{32} with varying values of the index of refraction. The result was that a 10% increase in the index of refraction will increase the "measured" D_{32} by approximately 10%. This could present difficulties if the present technique were attempted to be applied to a wide range of propellants/operating conditions where the unknown exhaust gas index of refraction could vary significantly from test-to-test. In the present effort similar propellant compositions are used with varying solids size and loading and with varying nozzle geometries. Variations in the index of refraction should be small in this case.

A small motor firing was made in which the scattered light was measured both in the nozzle exhaust jet (2.75 in. aft of the nozzle) and within the motor (just forward of the exhaust nozzle). This motor used the RPL-GAP propellant in a grain which was cylindrically perforated and with the aft-end uninhibited. Eight photodiode array scans were made in the exhaust and four were made through the motor. Using the techniques discussed above it was found that D_{32} was approximately $20\mu\text{m}$ in the motor (the same as the mean powder size in the propellant) and $62\mu\text{m}$ in the exhaust. The large exhaust particle size was unexpected and is currently being compared to size data obtained from collected exhaust products. However, post-fire examination of the motor revealed that considerable particulate matter was deposited on the converging section of the copper exhaust nozzle. This could readily result in large particles passing out into the exhaust jet.

HOLOGRAPHIC INVESTIGATION USING A TWO-DIMENSIONAL MOTOR

INTRODUCTION

In earlier studies at NPS² using the 2-D slab motors, many holograms were required to get one good hologram. Even when a minimum amount of inhibitor is used, the slab burners have a high ratio of inhibitor mass to propellant mass. This can result in excessive amounts of inhibitor char in the gases during propellant burning. Too little inhibitor can result in the glass cracking too early during the burn. These effects can result in rapid changes in the opacity of the combustion products during the burn. This, in turn, causes rapid changes in the scene beam light intensity which reaches the holographic plate. In order to obtain a higher success rate for obtaining good holograms, a series of tests were conducted to determine the effects of binder thickness, propellant thickness, binder composition and aluminum content on transmittance vs. burn time.

These parameters were systematically varied in a test series while measuring transmittance using a He-Ne laser and a photodiode.² Thicker inhibitor resulted in too much smoke while the glass would crack or side burning would occur with thinner inhibitor. With 5% metallized propellants burned at 500 psia, transmittance values were typically 2-5% within 0.2 seconds after steady state combustion was reached. This was true for both HTPB and GAP binders. For these propellants a maximum propellant slab thickness was approximately 2mm. When the metal content was increased to 10% and 15%, transmittance was reduced to between 0 and 1%. This implied that holograms would be very difficult to obtain with these metal levels using the present 2-D geometry and construction techniques.

These results were used in the holographic investigation to provide both the optimum time to take the hologram during the burn and the required reference beam attenuation to obtain the proper scene beam to reference beam intensity ratio on the holographic plate.

Basic 2-D motor dimensions, and construction and testing techniques were unchanged from those used in the earlier studies.²

RESULTS AND DISCUSSION

Table II presents the major ingredients of each of the propellants studied. They included both GAP and HTPB propellant binders with about 5% aluminum, HTPB binder with up to 15% aluminum and varying sizes of aluminum powder from 6- $82\mu\text{m}$. Also, two HTPB propellants were tested with stability additive (WGS-G, WGS-ZrC).

Resolution limits were generally determined using the Air Force resolution chart in place of the propellant in the combustion bomb. However, additional calibrations were made by taking holograms of spherical glass beads of known size. Fig. 5 is a photograph of a reconstructed hologram of glass beads with diameters between 55 and $63\mu\text{m}$. Current resolution limits are approximately $9\mu\text{m}$.

A representative photograph of a reconstructed hologram is shown in Fig. 6. Good quality holograms were obtained with all propellants containing less than 5% metal additive to pressures of approximately 880 psia (the maximum attempted). However, the approximately $7\mu\text{m}$ aluminum size in propellant WGS-7 was below the resolution limit of the currently employed diffuse illumination holograms. A good hologram was also obtained with 10% aluminum at approximately 500 psia. These holograms were obtained with very few repeat tests. This was made possible by using the data discussed above (for transmittance vs. burn time, propellant thickness and inhibitor thickness) to optimize the light intensity and intensity ratio reaching the holographic plate.

No holograms could be attained with 10% aluminum at 800 psia or with 15% aluminum in the propellant. The 2-D motor construction method has proven to be quite good within the limits presented above. Impingement of the particulates on the glass walls and a high inhibitor to propellant mass ratio have provided the upper limits in metal content and propellant thickness in the tests. Holograms may actually be more easily obtained in a 3-D motor. In that case, although the scene depth is greater, both of the above limitations can be significantly reduced.

TABLE II
Propellant Compositions

Propellant Designation	Binder % Weight	Oxidizer % Weight	Metal % Weight	Mean metal Diameter, μm
WGS-5A*	HTPB 12	AP 83	AL 5	75-88
WGS-6A*	HTPB 12	AP 83	AL 5	45-62
WGS-7A*	HTPB 12	AP 83	AL 5	23-37
WGS-7*	HTPB 12	AP 83	AL 5	6-7
WGS-9*	HTPB 12	AP 78	AL 10	23-27
WGS-10*	HTPB 12	AP 73	AL 15	23-27
RPL-GAP	GAP/TEGTM 14.7/8.5	AP 70.3	AL 4.7	20
WGS-G	HTPB 14	AP 84	G 2	50x20x7, flakes
WGS-ZrC	HTPB 14	AP 84	ZrC 2	23, irregularly shaped

* 65 % 180 μm / 35 % 26 μm

All propellants except RPL-GAP were provided by the Aerojet Solid Propulsion Company.

AUTOMATED RETRIEVAL OF PARTICLE DATA FROM HOLOGRAMS

Automatic retrieval of particulate diameter data from the reconstructed holograms is required if meaningful amounts of data are to be realized in a reasonable period of time. Suggested techniques have ranged from complete digitization with subsequent computer processing to man-in-the loop optical methods. A reasonable near-term method for our purposes appears to be a combination of the optical and digital methods. The technique centers around a Quantimet 720 image processing system. This system is a hybrid system that performs analog processing on a video image of the reconstruction plane. Various modules are available to apply manipulation of the grey-scales for contrast enhancement and various sizing tests to measure such features as particle area and diameter subject to a variety of logical tests that can be used to discriminate particles with desired features from the background or from other particles. Either raw video or processed video (or a superposition of both) can be viewed on the screen. The system has been currently set up under manual control. A test photograph of a hologram reconstruction was used for operator training purposes in the initial effort². Recently, the system has been used to image reconstructions from a hologram, again under manual control.

The holocamera is mounted on a remotely controlled xyz stage for acquisition of the desired on of the reconstruction by a plumbicon camera looking through a microscope with objective powers of 1:1, 5:1, or 10:1. Gross focussing is done through manual adjustment of the microscope mount; fine adjustment is done with the stage controller which is capable of motions of sizes that range from as large as a few millimeters to as small as 0.1 micrometers in each axis. The hologram reconstruction volume is typically 1.5 to 2.0 mm in depth.

Holograms of resolution charts with various recording geometries were recorded as described in an earlier section for the purpose of measuring system resolution. Additionally, reconstructions of a 2-D motor burning propellant WGS-7A at a pressure of 745 psia were examined for particle identification. The operator can choose to focus on particles at various depths in the reconstruction volume. Significant amounts of char and impinged particles are evident on the front and back windows of the hologram. These latter problems may be eliminated with current attempts at obtaining holograms within a small, three-dimensional motor which incorporates purged windows.

A primary problem in the reconstruction is the effect of speckle in the image. The holograms are recorded with diffuse coherent illumination to eliminate schlieren effects from the temperature gradients surrounding the burning particles. This diffuse illumination implies that the image will

have a speckle background in the reconstruction of the hologram. The speckle can have two effects. First, the maximum size of the observed speckle can be comparable to (or larger than) the observed particles. The size of the imaged speckle depends on the illumination geometry of the recording process and the lenses in the reconstruction process. Work is proceeding on identifying sources of large speckle with the goal of minimizing the speckle size in the image. The second effect of speckle is to reduce the contrast between a particle and the background. The speckle pattern can be reduced by superposition of several images with differing speckle patterns. (The result of superpositioning N images with independent speckle patterns is an improvement in particle-to-speckle contrast of $N^{1/2}$.) One way to change the speckle pattern is to form an image of the reconstruction on a rotating diffuse disk transparency. The speckle is blurred due to rotation during the integration time of the camera tube while the particle and object features remain unchanged. The scan time of the slow-scan television camera in the Quantimet is 0.1 sec. Fig. 7 shows the image form on a stationary mylar screen. Fig. 8 shows the same image with the mylar rotating. The speckle reduction is apparent.

Fig. 9 shows the reconstructed image (with a rotating mylar disk screen) with some manipulation of the grey-scales in a digitized image. The higher intensity levels of the speckle have been hard-limited to maximum brightness while the darker regions of the objects (and the darkest regions of the speckle pattern) remain. Some degree of reduction in the effects of the speckle are evident but some interpretative ability on the part of the operator is required to avoid mislabeling the speckle artifacts as objects. Longer integration times of the imaging system or increased rotation rates of the moving mylar screen should reduce this problem.

An option on the Quantimet also allows computer control of the modules combined with direct data transfer of the digitized (or processed) image. This option is currently being implemented under the control of a PDP 11/04 minicomputer. Eventually, the xyz stage will be computer-controlled as well. The goal of the computer-controlled processing system, besides software control of the Quantimet processing, is the capability to process multiple images from the same reconstruction. This would be useful in investigating digital techniques for speckle reduction and particle counting in a frame-to-frame manner to allow the entire reconstruction volume to be investigated.

CONCLUSIONS

The high speed motion picture techniques have resulted in excellent quality films of burning propellant strands in which the flame envelopes surrounding the burning particles are practically eliminated.

An apparatus has been developed which uses dual-beam measurement of diffractively scattered light to determine the change in D_{32} across an exhaust nozzle. The apparatus and data reduction techniques have been validated using precision spherical glass beads and aluminum oxide powder. Initial tests have resulted in measurements of realistic in-motor particle size. Final validation is currently being made using collected exhaust particulates.

The small two-dimensional motor can be used to obtain good quality holograms of the particulate in a cross-flow environment within specified ranges of operating pressure and metal content.

The development of a technique for automatic retrieval of particulate data from holograms has progressed to the point where reconstructed images of the hologram can be remotely positioned, viewed and analyzed on the Quantimet image analyzer. Present efforts are directed at techniques for speckle suppression and obtaining data from scans throughout the depth of the holographic scene.

REFERENCES

1. Karagounis, S. G.; Dilorieto, V. D.; Gillespie II, T. R.; Dubrov, E.; Hickey, P. J. and Netzer, D. W., "An Investigation of Experimental Techniques for Obtaining Particulate Behavior in Metallized Solid Propellant Combustion," Naval Postgraduate School, Air Force Rocket Propulsion Laboratory Report, AFRPL-TR-82-051, July 1982.
2. Cramer, R. G.; Edington, R. J.; Faber, D. E.; Graham, K. J.; Hansen, B. J.; Hickey, P. J.; Klooster, L. A.; Mellin, P. J.; Powers, J. P. and Netzer, D. W., "An Investigation of Experimental Techniques for Obtaining Particulate Behavior in Metallized Solid Propellant Combustion," Naval Postgraduate School, Air Force Rocket Propulsion Laboratory Report, AFRPL-TR-84-014, February 1984.
3. Buchele, D. R., "Particle Sizing by Measurement of Forward-Scattered Light at Two Angles," NASA TP 2156, May 1983.
4. Van de Hulst, H. C., Light Scattering by Small Particles, Dover Publication, Inc., 1981.
5. Dobbins, R. A.; Crocco, L., and Glassman, I., "Measurement of Mean Particle Size of Sprays from Diffractively Scattered Light," AIAA J., Vol. 1, No. 8, August 1963, pp. 1882-1886.

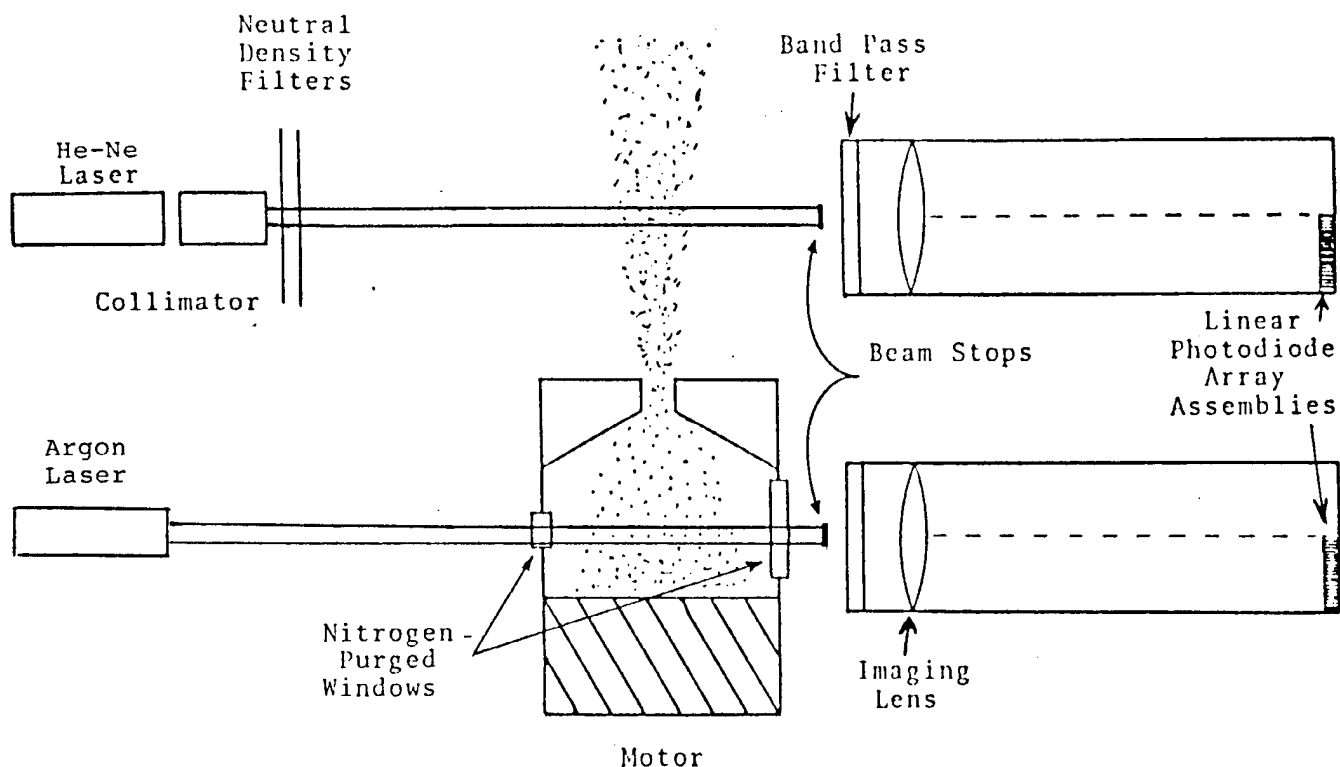


Figure 1. Schematic of Light Scattering Apparatus.

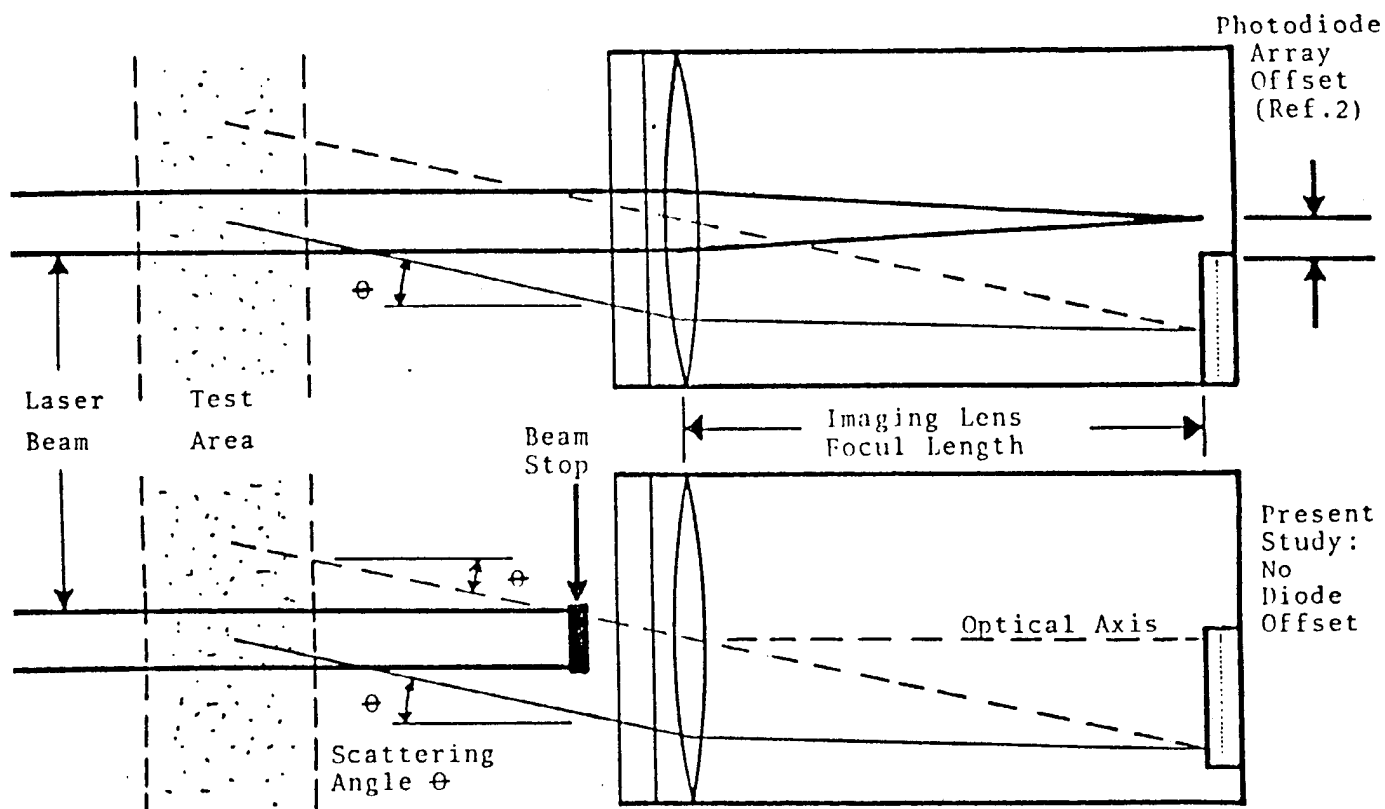


Figure 2. Comparison of Two Geometries for Light Scattering Measurements.

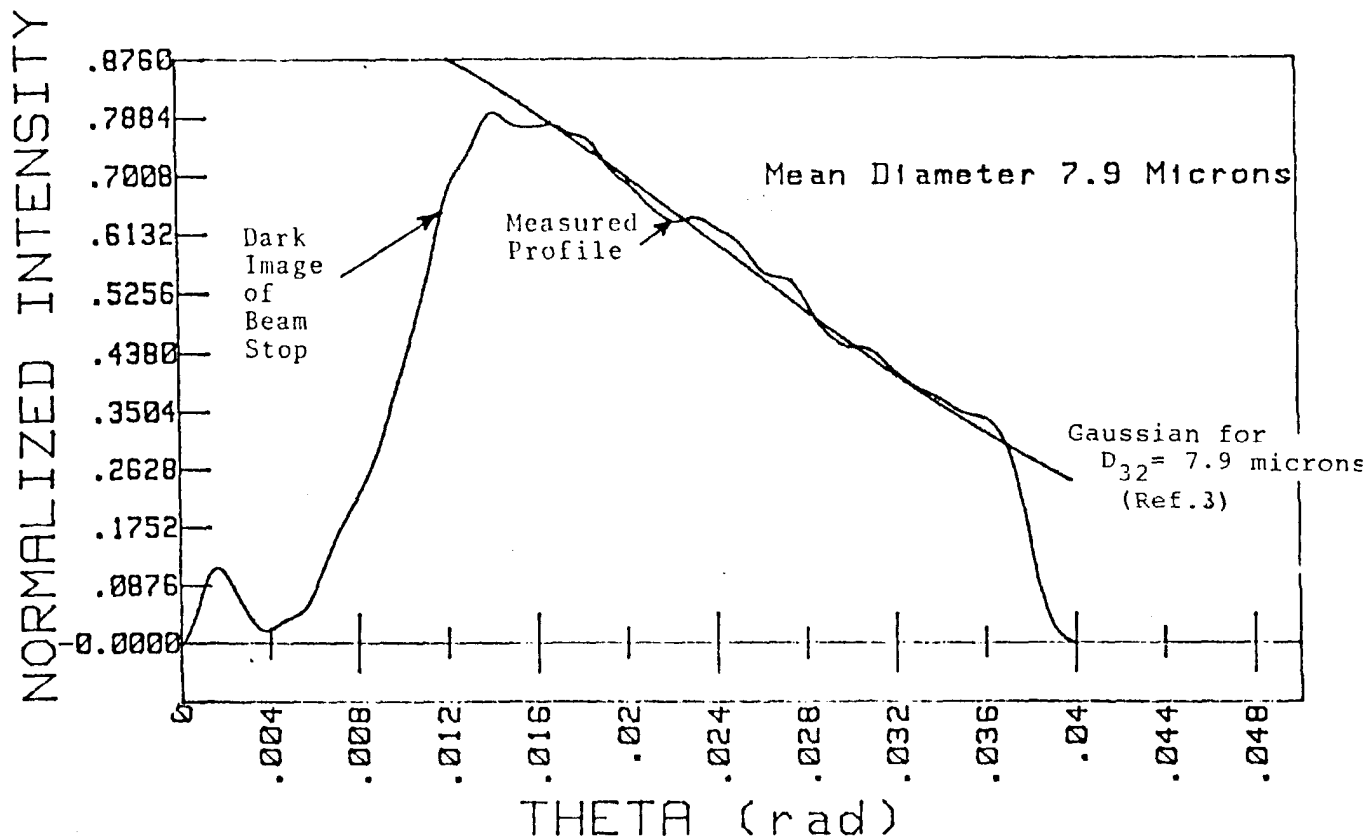


Figure 3. 1-16 Micron Polystyrene, Curve Fit.

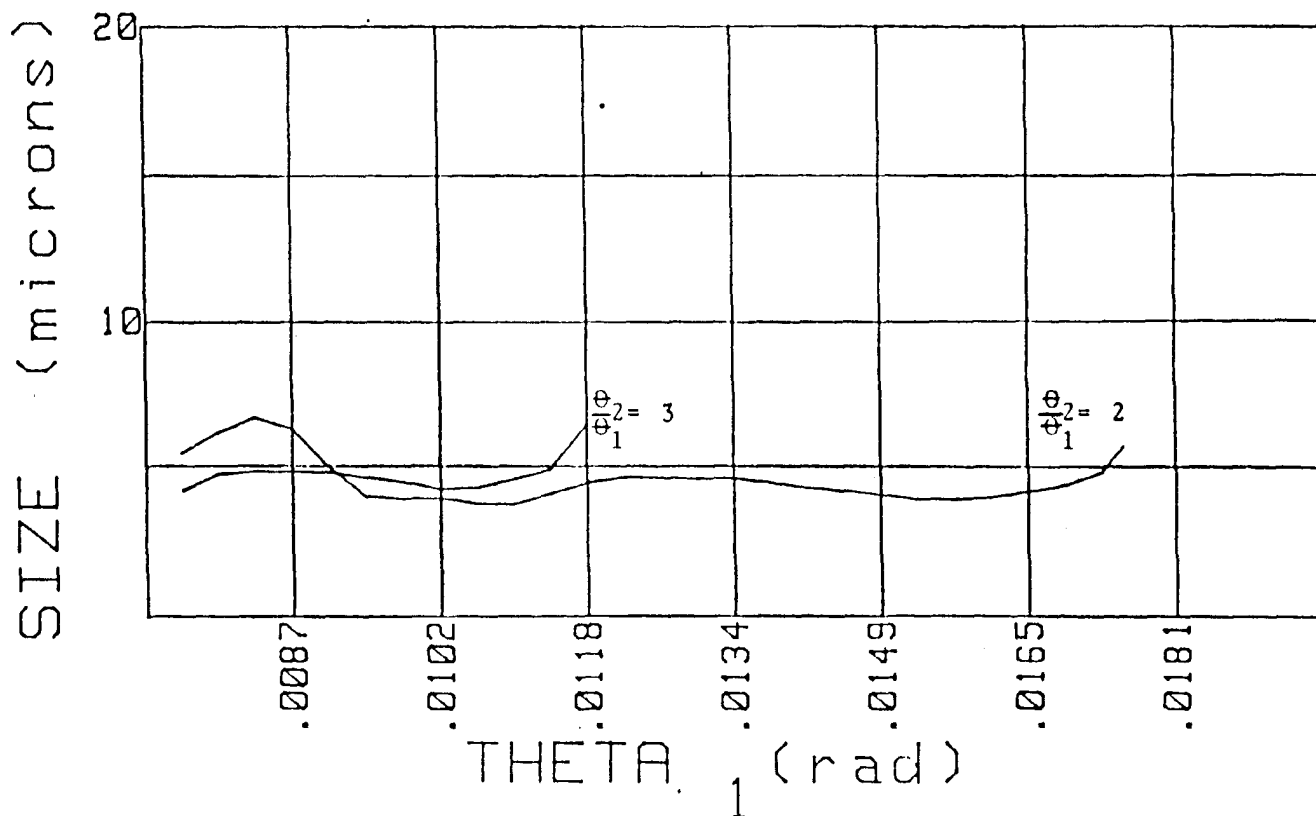


Figure 4. 3-6 Micron Polystyrene, Two Angle Method [Ref. 3].

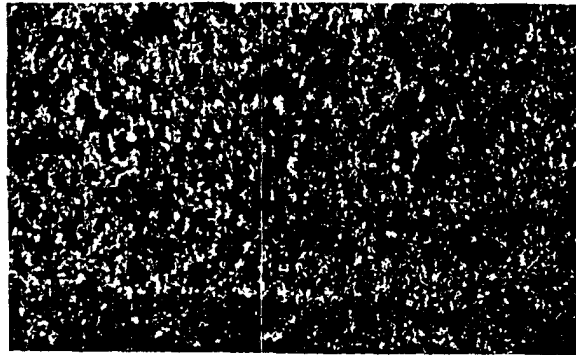


Figure 5 Photograph of Reconstructed
(Diffuse Illumination) Hologram
of 53-63 μm Glass Beads.



Figure 6 Photograph of Reconstructed Hologram of
Propellant WGS-5A Burned at 405 psi in
Two-Dimensional Motor.

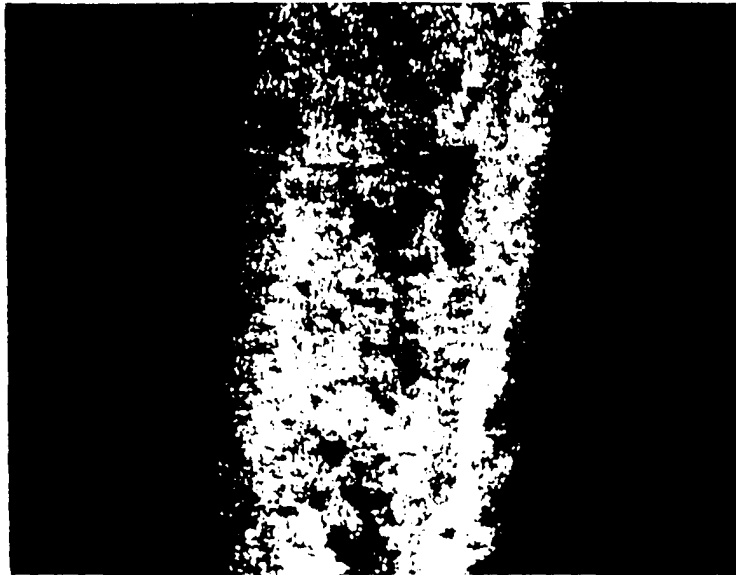


Figure 7 Photograph of the Q720 Screen Image of a Reconstructed Hologram of Propellant WGS-7A Burned at 745 psi in a Two-Dimensional Motor. Mylar Disk Stationary, Raw Video.



Figure 8 Photograph of the Q720 Screen Image of a Reconstructed Hologram of Propellant WGS-7A Burned at 745 psi in a Two-Dimensional Motor. Mylar Disk Rotating, Raw Video.



Figure 9 Photograph of the Q720 Screen Image of a
Reconstructed Hologram of Propellant WGS-7A
Burned at 745 psi in a Two-Dimensional Motor.
Mylar Disk Rotating, Grey-Scales Manipulated.